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Enlarge duct length optimization for suddenly expanded flows

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Abstract. In many applications like the aircraft or the rockets/missiles, the flow from a nozzle needs to be expanded suddenly in an enlarged duct of larger diameter. The enlarged duct is provided after the nozzle to maximize the thrust created by the flow from the nozzle. When the fluid is suddenly expanded in an enlarged duct, the base pressure is generally lower than the atmospheric pressure, which results in base drag. The objective of this research work is to optimize the length to diameter (L/D) ratio of the enlarged duct using the CFD analysis in the flow field from the supersonic nozzle. The flow from the nozzle drained in an enlarged duct, the thrust, and the base pressure are studied. The Mach numbers for the study were 1.5, 2.0 and 2.5. The nozzle pressure ratios (NPR) of the study were 2, 5 and 8. The L/D ratios of the study were 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10. Based on the results, it is concluded that the L/D ratio should be increased to an optimum value to reattach the flow to an enlarged duct and to increase the thrust. The supersonic suddenly expanded flow field is wave dominant, and the results cannot be generalized. The optimized L/D ratios for various combinations of flow and geometrical parameters are given in the conclusion section.

Keywords: base pressure; length to diameter ratio; mach number; nozzle pressure ratio; thrust

1. Introduction

In high-speed suddenly expanded flow fields, the base pressure reduces in several aerospace applications, such as rocket, missile, space shuttle, bomb, and has been the subject of many investigations for several years.

Mehta and Natarajan (2014) have studied the flow field from a supersonic nozzle, and they have considered the L/D ratio as 5 in their research work. Kuzmin and Babarykin (2018) have studied airflow and shock wave in a rectangular channel and demonstrated the Mach number distribution. Allison *et al.* have addressed the challenges in designing aircraft for the long-range mission. Kuzmin (2019) studied shock wave instability numerically and shows that the shock wave instability is caused by the interaction of shocks with duct walls. Candon *et al.* (2015) have studied parameters and their effect on thrust for scramjet nozzle. The nature of the flow field with the sudden expansion is shown in Fig. 1 (Pathan *et al.* 2019b). The base pressure is

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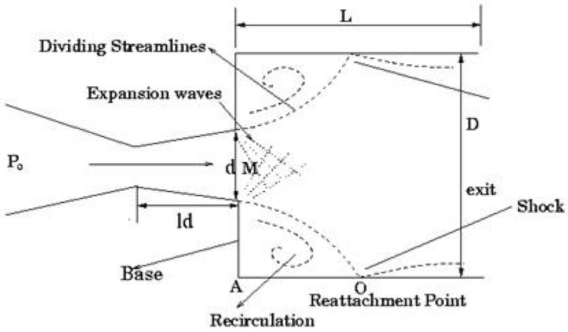

Fig. 1 Suddenly expanded flow field

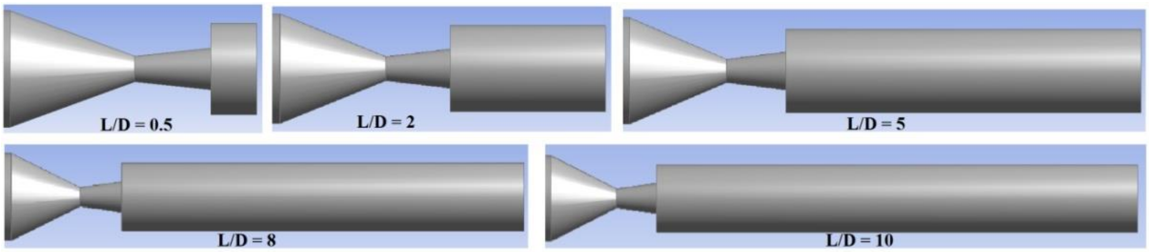

Fig. 2 Geometry for various L/D ratios

reduced when the flow from the supersonic nozzle is suddenly expanded into an enlarged duct. The reattachment point is a location where the flow strikes the duct wall, and the corresponding length is known as reattachment length.

The enlarged duct with sufficient length should be provided after the nozzle so that the fluid exiting from the nozzle should reattach to the enlarged duct. Based on the literature, it is well understood that the reattachment length increases with an increase in flow Mach number. The level of expansion of flow exiting from the nozzle increases with an increase in the nozzle pressure ratio (Pathan *et al.* 2019b, c, d).

It is well understood that the high–speed aerodynamic flow introduces many unwanted separation characteristics, such as very unsteady pressure fluctuations, a vital thrust loss due to flow entrainment, and so on studied by (Khan *et al.* 2018, Asadullah *et al.* 2018a, 2018b). The internal and external suddenly expanded flow field has principally the same base pressure variations (Hoerner 1949, Pathan *et al.* 2019a). The different shapes of the human-powered submarine have been studied and found the optimum fineness ratios by (Khan *et al.* 2018). (Pathan *et al.* 2019a, b, c) have studied various parameters affecting on base pressure and the thrust. These flow-induced influences can reduce the performance of the rocket, missile, space shuttle, aerospace vehicle, etc. Efforts to develop more efficient aerodynamic vehicles have been correlated by similar attempts to understand and to reduce these unwanted effects of base flow aerodynamics (Aabid *et al.* 2019). The area ratio of an enlarged duct is optimized based on the thrust and base pressure. The area ratio of an enlarged duct should be in the range of 4 to 6 (Pathan *et al.* 2018a). An investigation has been conducted to increase base pressure by active control method and found that the control jets are useful to increase base pressure (Pathan *et al.* 2018b, 2019a, b).

An enlarged duct is provided to guide the flow exiting from the supersonic nozzle for maximizing the thrust. In this research paper, the research work was started with the intention of both developing a better understanding of the thrust and base pressure fluctuations, and investigation of the influence of flow and geometrical parameters on base pressure and thrust. In this research paper, various cases have been analyzed by varying length to diameter ratio, NPR, and Mach numbers to find the minimum duct length to maximize thrust.

In the literature, many investigations have been studied in the same field by considering some fixed length to diameter ratio. The supersonic flow field is wave dominant, and the minimum L/D ratio required for various combinations of parameters like Mach number, NPR, etc. cannot be generalized. In this research paper, the optimized length of the enlarged duct for every case has studied and clearly mentioned, which is an advantage of this research work over existing literature.

2. Factorial design for three factors with multi levels

The full factorial design is used to make all the possible combinations of the factors and levels. The CFD analysis was carried out for a total of 99 combinations of factors with their various levels. The L/D ratios considered for the analysis were 0.5 to 10 along with Mach numbers 1.5, 2.0 and 2.5 and nozzle pressure ratios 2, 5 and 8. The responses in the form of thrust and the base pressure are recorded for all the cases. All the base pressure values are converted into dimensionless base pressure by adding ambient atmospheric pressure and by dividing the sum by ambient atmospheric pressure. The dimensionless base pressure is calculated for all the cases and plotted in the graphs, as discussed in the below sections.

3. Modeling and meshing

The several geometries are modeled for all the possible combinations of Mach numbers, NPR, and L/D ratios. Fig. 2 shows geometry with L/D ratios 0.5, 2.0, 5.0, 8.0 and 10.0. The face at the base of the enlarged duct is named as a base face, and it is defined as a wall in Fluent during analysis. The base face is used to calculate an average base pressure during post-processing. The entire structured mesh is generated by dividing the geometry into many parts, and each part has meshed separately with a structured meshing scheme.

4. CFD Analysis and results

The CFD analysis is based on the fundamental governing equations of fluid dynamics – the continuity, the momentum, and the energy equations. They are the mathematical equations of three fundamental physical principles upon which all of fluid dynamics is based.

1. Mass is conserved (the Continuity equation)
2. Newton's second law (Momentum equation)
3. Energy is conserved (Energy equation)

The equations considered for a fluid flow analysis are continuity equation, momentum equation, and energy equation are given in Eqs. (1)-(6).

Under the dynamic conditions when the medium is moving, the characteristic feature for incompressible and compressible flow situations are:

The volume flow rate is even at each cross-section of a stream tube for incompressible flow.

$$\dot{Q} = AV \tag{1}$$

The mass flow rate is constant at any cross-section of a stream tube for compressible flow.

$$\dot{m} = \rho AV \tag{2}$$

where,

A is cross-sectional area if stream tube,

V and ρ are velocity and density of the fluid, respectively, at that cross-section.

For three dimensional compressible flow $div(\rho V) = 0$

$$\text{i.e., } \frac{\partial(\rho U_x)}{\partial x} + \frac{\partial(\rho U_y)}{\partial y} + \frac{\partial(\rho U_z)}{\partial z} = 0 \tag{3}$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{4}$$

The momentum equation and energy equations are given in Eqs. (5) and (6).

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_i} = \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\tau_{ij} \tag{5}$$

$$\frac{\partial}{\partial t}\left[\rho\left(e + \frac{V^2}{2}\right)\right] + \frac{\partial}{\partial x_j}\left[\rho u_j\left(e + \frac{V^2}{2}\right) + P + q_j - u_i\tau_{ij}\right] = 0 \tag{6}$$

where,

u is instantaneous velocity,

V is velocity modulus,

ρ is gas density,

P is gas pressure,

q_j is heat flux and

τ_{ij} is viscous stress tensor.

The enlarged ducts of various L/D ratios were attached to the nozzle of various Mach numbers. The nozzle pressure ratios were varied to examine all the possible combinations of parameters. The CFD analysis was carried out to find the minimum duct length needed to give the highest thrust and to find the best L/D ratio so that the flow should reattach to the enlarged duct.

The boundary conditions were set at the inlet and exit. The inlet and outlet boundary condition was defined for the inlet of the nozzle, and the pressure, which was more than ambient pressure was set as per the NPR. The exit of the enlarged duct was defined as pressure outlet, and the gauge pressure was set at zero. The CFD analysis was carried out for all the combinations of parameters, and the result of the study are correlated.

The grid independence test is essential to ensure the simulation results are not affected by the

Table 1 Grid independence test for various mesh sizes

Mesh Max Size (mm)	Mesh Elements	Static Pressure at Base Edge	Total Pressure at Base Edge
5	56	0.982321125	0.983963473
4	92	0.924344944	0.92464879
3	162	0.860645547	0.862173393
2	352	0.878006385	0.881550664
1	1310	0.885458179	0.886654320
0.8	2030	0.883369159	0.884080365
0.6	3609	0.885199250	0.886767540

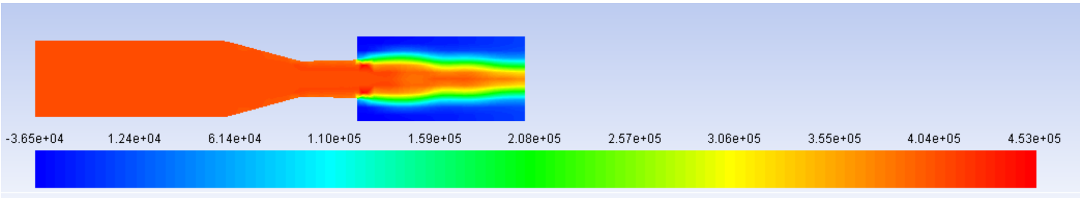

Fig. 3 The Pressure contour (in Pascal) for NPR = 5, M = 1.5 and L/D = 2

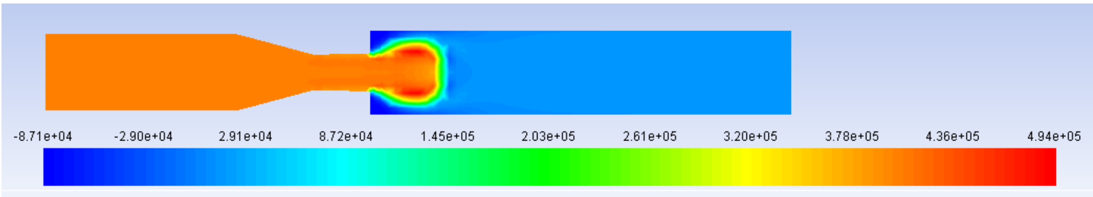

Fig. 4 The Pressure contour (in Pascal) for NPR = 5, M = 1.5 and L/D = 5

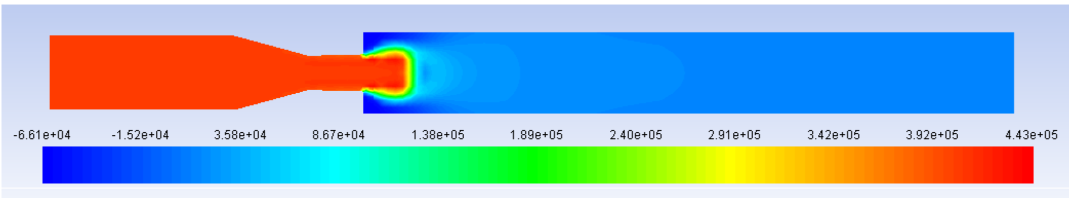

Fig. 5 The Pressure contour (in Pascal) for NPR = 5, M = 1.5 and L/D = 8

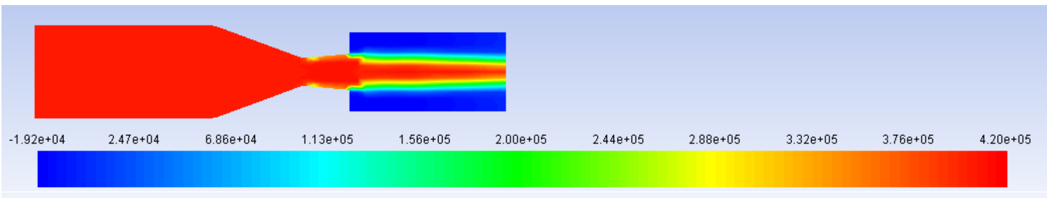

Fig. 6 The Pressure contour (in Pascal) for NPR = 5, M = 2.0 and L/D = 2

grid size. Based on the grid independence test for the model is shown in Table 1, the mesh element size of 1 mm or less is not affecting the results. Hence the mesh element size of 1 mm is

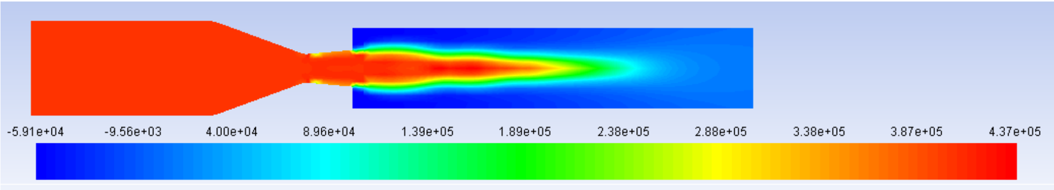

Fig. 7 The Pressure contour (in Pascal) for NPR = 5, M = 2.0 and L/D = 5

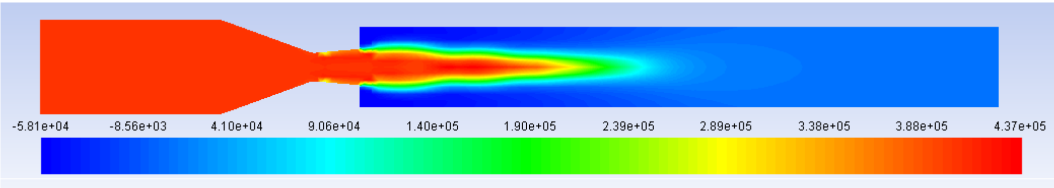

Fig. 8 The Pressure contour (in Pascal) for NPR = 5, M = 2.0 and L/D = 8

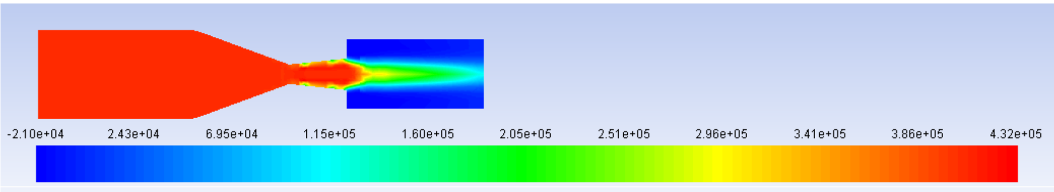

Fig. 9 The Pressure contour (in Pascal) for NPR = 5, M = 2.5 and L/D = 2

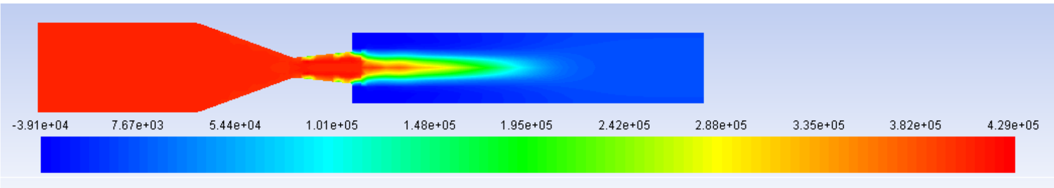

Fig. 10 The Pressure contour (in Pascal) for NPR = 5, M = 2.5 and L/D = 5

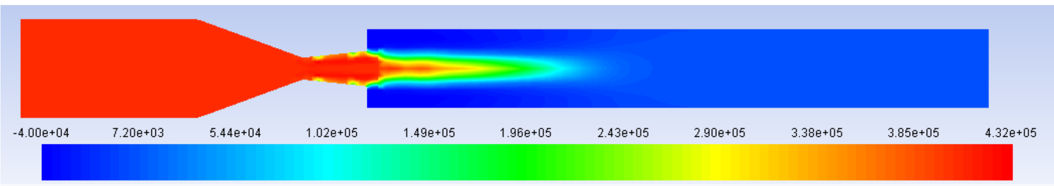

Fig. 11 The Pressure contour (in Pascal) for NPR = 5, M = 2.5 and L/D = 8

considered for the CFD analysis.

The contours of total pressure are plotted using a Fluent postprocessor. The pressure contours for L/D ratio 2, 5, and 8 with Mach numbers 1.5, 2.0, and 2.5 at constant NPR = 5 are shown in Figs. 3-11.

The nozzle pressure ratio required to correctly expand the main jet at Mach numbers 1.5, 2.0, and 2.5 is 3.67, 7.82, and 17.09 respectively. From Figs. 3-11 it is observed that the pressure in the base region of the duct is remarkably lower than the atmospheric pressure at higher L/D ratios.

Figs. 3-5 show the under–expanded conditions while Figs. 6-11 show the over–expanded conditions. For under expanded conditions, the lower L/D ratio is sufficient to reattach the main jet to the enlarged duct, but the increment in L/D does not affect adversely. For over–expanded conditions, the higher L/D is required to reattach the main jet to the enlarged duct. The optimum L/D required to maximize the thrust and to reattach the main jet to the enlarged duct is discussed in detail in the followings sections.

4.1 Optimization of L/D ratio based on base pressure and reattachment

The average base pressure is calculated on the base face of the enlarged duct with the help of ANSYS Fluent post-processor. The plots for dimensionless base pressure vs. Mach number at various L/D ratios are plotted in Figs. 12-14.

Fig. 12 shows base pressure vs. Mach number for various L/D ratios at NPR = 2. From Fig. 12 it can be observed that at L/D = 0.5 and 1, the flow from the nozzle does not reattach to the enlarged duct and the base area is open to the atmosphere, because of which the base pressure is almost the same as the atmospheric pressure at all the Mach numbers. At Mach number 1.5 and NPR = 2, the main jet is over–expanded, and due to the low level of expansion and low inertia level the main jet is partially reattached to the enlarged duct from L/D ratios 2 to 10, and the base pressure is marginally lowered in the base area. At Mach numbers 2.0 & 2.5, the main jet is over-expanded. Because of the high inertia level (Mach number), the flow does not reattach to the enlarged duct. The change in the base pressure is marginal for L/D = 2 to 10 at Mach number 2.0 and L/D = 1 to 10 at Mach number 2.5. Hence the base pressure is almost the same as ambient atmospheric pressure.

Fig. 13 shows base pressure vs. Mach number for various L/D ratios at NPR = 5. From Fig. 13 it is seen that, at L/D = 0.5 and 1, the flow from the nozzle does not reattach to the enlarged duct and the base region is open to the atmosphere because of which the base pressure is almost the same as the atmospheric pressure at all Mach numbers. At Mach number 1.5 and NPR = 5, the main jet is under–expanded, and the main jet is partially reattached to the enlarged duct even at lower L/D ratios, i.e., L/D = 2 and 3, and the base pressure is slightly reduced. At L/D = 4 or higher, the flow is entirely reattached to the enlarged duct, and the base pressure is decreased significantly. At Mach number 2.0 and 2.5 and NPR = 5, the main jet is over–expanded, and the flow is partially reattached to the enlarged duct at L/D = 4 or higher.

Fig. 14 shows base pressure vs. Mach number for various L/D ratios at NPR = 8. From Fig. 14 it is discerned that at L/D = 0.5 and 1, the flow from the nozzle does not reattach to the enlarged duct, and the base region is open to the atmosphere because of which the base pressure is almost same as the atmospheric pressure. At Mach number 1.5 and NPR = 8, the main jet is under–expanded, and the main jet is partially reattached to the enlarged duct even at lower L/D ratios, i.e., L/D = 2 and 3. The values of the base pressure for Mach number 1.5 at L/D = 2 and 3 are higher as compared with higher L/D ratios (L/D = 4 or higher), because, at Mach number = 1.5 and NPR = 8, the nozzle is highly under-expanded, and for L/D = 2 or 3 the main jet is partially reattached to the enlarged duct and partially opened in the atmosphere. At Mach number 2.0 and NPR = 8, the main jet is under–expanded, and the flow is partially reattached to the enlarged duct even at L/D = 2. With the increase in the enlarged duct length, the base pressure gets lowered as shown in Fig. 14 for L/D = 2 to 3 at Mach number 2.0. At Mach number 2.5 and NPR = 8, the main jet is over–expanded, and the flow does not completely reattach to the enlarged duct from L/D = 0.5 to 4. At L/D = 5 or higher, the flow is completely reattached to the enlarged duct, and base pressure is reduced.

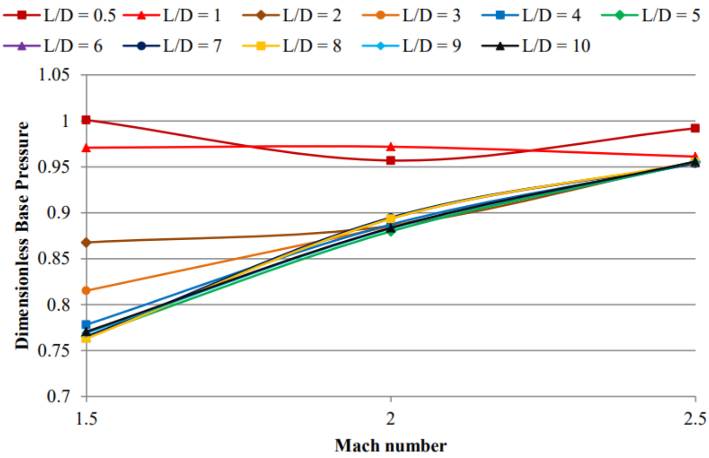

Fig. 12 Base pressure vs Mach number for various L/D ratios at NPR = 2

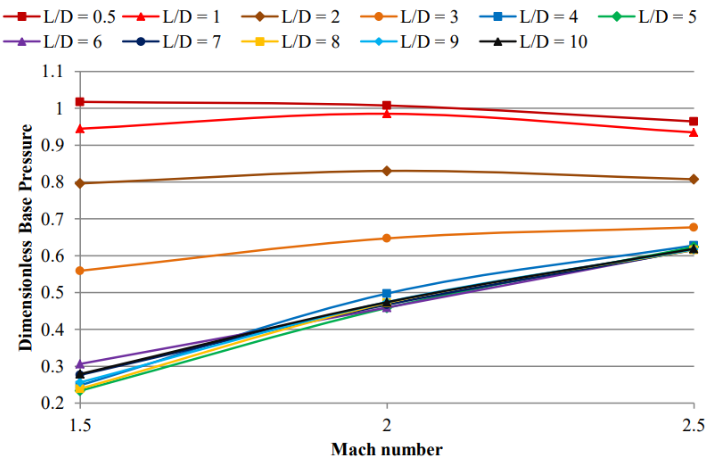

Fig. 13 Base pressure vs Mach number for various L/D ratios at NPR = 5

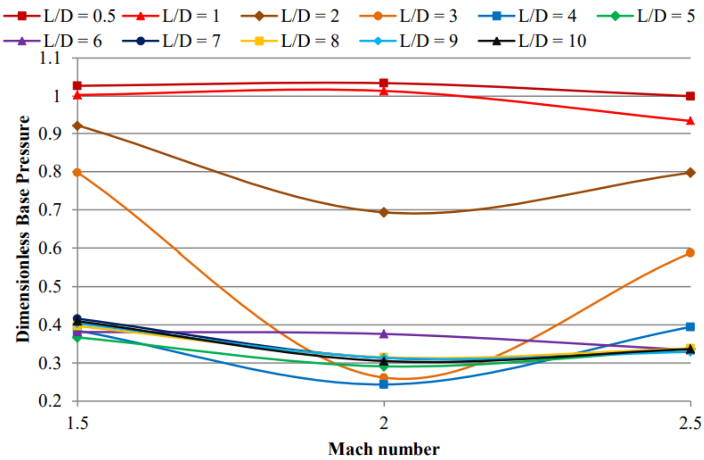

Fig. 14 Base pressure vs Mach number for various L/D ratios at NPR = 8

4.2 Optimization of L/D based on thrust

While considering the flow from converging-diverging nozzles, the essential parameters which is of imminence are the thrust in the case of space and defense application. Figs. 15-17 show the effect of the L/D ratio at various Mach numbers and nozzle pressure ratios on the thrust in the axial direction. The thrust created by the flow from the converging-diverging nozzle depends on the flow rate, velocity, exit area of the nozzle, and the exit pressure. The thrust force from the C-D nozzle can be calculated using Eq. (7).

$$Thrust\ \ (T) = \dot{m}_j v_j + A_e(p_e - p_a) \tag{7}$$

where,

$\dot{m}_j$ is the mass flow rate of the main jet
v_j is the velocity of the main jet
A_e is the nozzle exit area
p_e is the nozzle exit pressure
p_a is atmospheric pressure

Fig. 15 shows the thrust vs. Mach number for various L/D ratios at NPR = 2. From Fig. 15 it is observed that, at Mach number 1.5, with an increase in L/D ratio from 0.5 to 4, the thrust increases. At Mach number 2.0, with an increase in L/D ratio from 0.5 to 2, the thrust increases. At Mach number 2.5, with an increase in L/D ratio from 0.5 to 1, the thrust increases. If again, the L/D ratio increases, there is no change in the thrust at any Mach number. Because with an increase in the Mach number at lower nozzle pressure ratio, i.e., NPR = 2, the nozzle becomes highly over-expanded and for the highly overexpanded nozzle, the jet from the nozzle will flow in the axial direction without expanding. Hence the jet will not be affected by the enlarged duct length, and the jet will not be reattached to the enlarged duct at Mach number 2.5, which can be observed from Figs. 15 and 12.

Fig. 16 shows the thrust vs. Mach number for various L/D ratios at NPR = 5. From Fig. 16 it is noticed that, at Mach number 1.5 and 2.0, with an increase in L/D ratio from 0.5 to 4, the thrust increases. At Mach number 2.5, with an increase in L/D ratio from 0.5 to 3, the thrust increases. If

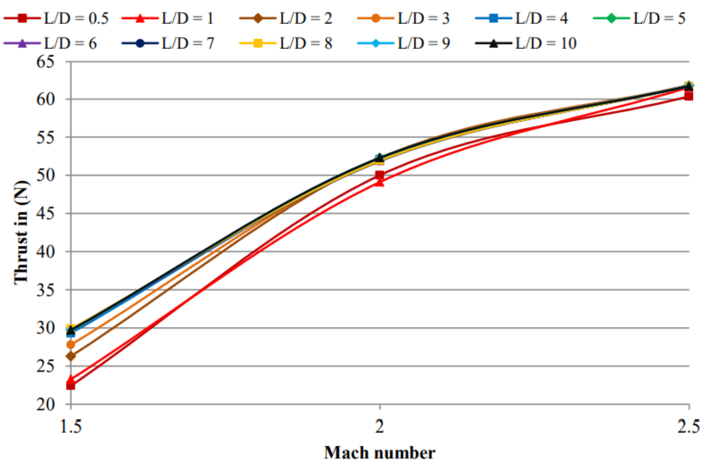

Fig. 15 Thrust vs. Mach number for various L/D ratios at NPR = 2

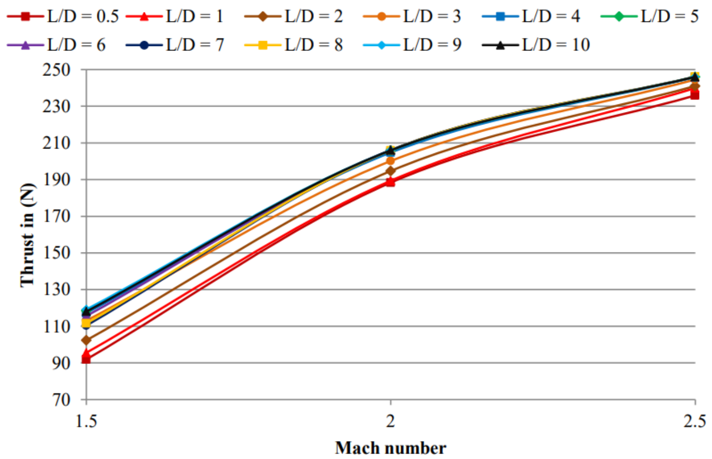

Fig. 16 Thrust vs. Mach number for various L/D ratios at NPR = 5

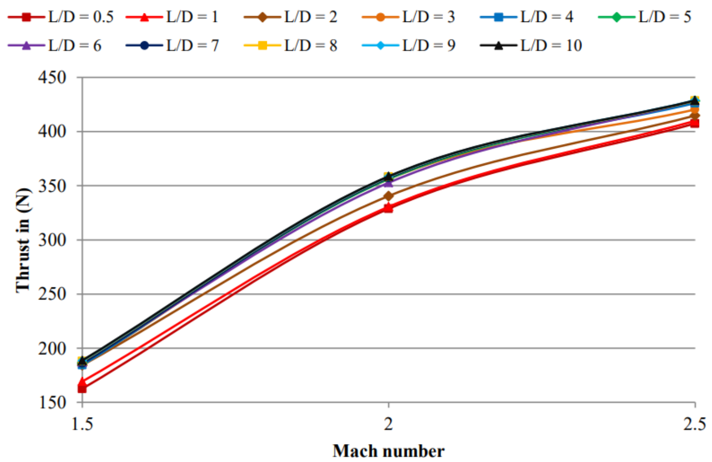

Fig. 17 Thrust vs. Mach number for various L/D ratios at NPR = 8

again, the L/D ratio increases, there is no change in the thrust at all the Mach numbers. Because with an increase in the Mach number at NPR = 5, the nozzle becomes over-expanded and for the overexpanded nozzle, the jet from the nozzle flows in the axial direction with a low level of expansion. Hence the jet is marginally affected by the enlarged duct length.

Fig. 17 shows thrust vs. Mach number for various L/D ratios at NPR = 8. From Fig. 17, it is noticed that, at Mach number = 1.5, with increment in L/D ratio from 0.5 to 2, the thrust increases. At Mach number 2.0, with increment in the L/D ratio from 0.5 to 3, the thrust increases. At Mach number 2.5, with increment in the L/D ratio from 0.5 to 4, the thrust increases. If again, the L/D ratio increases, there is no change in the thrust at all Mach numbers. At higher NPR (NPR = 8), the behavior of the thrust in a relation of L/D is entirely reversed as in the case of lower NPR (NPR = 2). Since at Mach numbers 1.5 and 2.0 and NPR = 8, the main jet is under–expanded, and the reattachment length reduced. As the reattachment length is reduced, the lower L/D ratios are sufficient to get the maximum thrust. At Mach number 2.5, the main jet is over–expanded, and for the over-expanded jet, the considerable length is required to reattach the flow. Hench at Mach number 2.5, the minimum L/D required to get maximum thrust is 4.

5. Conclusions

The enlarged duct plays a vital role in developing the thrust and the reattachment of the main flow while exiting from the nozzle. Based on results, it is observed that the thrust force increases with an increase in Mach number. It is also observed that the thrust increase with an increase in L/D ratio to some optimum value. However, in most of the cases, when the L/D ratio increases from 4 to 10, the change in thrust is marginal. Based on the results, it is concluded that the L/D ratio should be increased to a minimum value to increase the thrust.

Based on the results, the following conclusions may be drawn;

The minimum duct length to diameter ratio required to maximize the thrust for various combinations of flow and geometrical parameters are as follows;

• For nozzle pressure ratio = 2, the minimum L/D ratio at Mach number 1.5, 2.0, and 2.5 are 4, 2 and 1 respectively.

• For nozzle pressure ratio = 5, the minimum L/D ratio at Mach number 1.5, 2.0, and 2.5 are 4, 4 and 3 respectively.

• For nozzle pressure ratio = 8, the minimum L/D ratio at Mach numbers 1.5, 2.0, and 2.5 are 2, 3, and 4, respectively.

The minimum duct length to diameter ratio required to reattach to the main jet to an enlarged duct for various combinations of flow and geometrical parameters are as follows;

• For nozzle pressure ratio = 2, the minimum L/D ratio at Mach number 1.5, 2.0, and 2.5 are 2, 2 and 1 respectively.

• For nozzle pressure ratio = 5, the minimum L/D ratio at Mach number 1.5, 2.0, and 2.5 are 4.

• For nozzle pressure ratio = 8, the minimum L/D ratio at Mach numbers 1.5, 2.0 and 2.5 are 4, 3, and 4, respectively.

As the increase in duct length after a minimum value will not affects adversely, the most suitable value of the L/D ratio for each Mach number and NPR can be considered as 4.

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